Bidirectional reflectance distribution function and directional-hemispherical reflectance of a martian regolith simulant

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Abstract. Experimental data are presented on the bidirectional reflectance distribution function and 8-deg directional-hemispherical reflectance measurements of a Martian regolith simulant, JSC Mars-1. The scatterometer located in the National Aeronautics and Space Administration's Goddard Space Flight Center Diffuser Calibration Facility was used for the measurements reported. The data were obtained with a monochromator-based light source in the ultraviolet, visible, and near infrared spectral regions. The measurements were performed at different angles of incidence and over a range of in-plane and out-of-plane scattered geometries. The results presented are traceable to the National Institute of Standards and Technology. The hemispherical and diffuse scattering data obtained from these studies are important for current and future Mars space- and ground-based observations. [DOI: 10.1117/1.1870001]

Subject terms: Bidirectional reflectance distribution function; hemispherical reflectance; optical scattering; reflectance spectroscopy; remote sensing.

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1 Introduction

We present new results on the bidirectional reflectance distribution function (BRDF) and 8-deg directional-hemispherical reflectance of the Martian regolith simulant Johnson Space Center Mars-1 (JSC Mars-1), performed in the Diffuser Calibration Facility (DCaF) at NASA's Goddard Space Flight Center (GSFC). The facility scatterometer,[1] located in a class-10,000 laminar-flow clean room, is a fully automated instrument capable of measuring the BRDF and 8-deg directional-hemispherical reflectance of a wide range of sample types in the spectral range from 230 to 900 nm. The scatterometer can perform in-plane and out-of-plane BRDF measurements with a typical measurement uncertainty of less than 1% (coverage factor $k=1$). The experimental BRDF data were obtained with a monochromator-based Xe short-arc light source over a range of in- and out-of-plane incident and scattered geometries. Data on 8-deg directional-hemispherical reflectance were also measured and are reported here.

The planets are covered with a regolith layer that consists of minerals with differing composition, size, and shape. It is important to know their physical properties and how electromagnetic radiation interacts with these regolith layer components. The physics of incident light transmission, reflection, absorption, and multiple scattering by such regolith layers is complex and is difficult to understand and model. The BRDF characterization of planetary and terrestrial objects is often used in remote sensing applications. To date, a number of semiempirical models for analyzing the BRDF of particulate surfaces have been developed. The Hapke model[2–4] is most widely used in studies of the bidirectional reflectance of regoliths. Liang[5] has proposed a modified Hapke model, and Cord et al.[6] have proposed an optimized determination of Hapke parameters. Mishchenko[7] has indicated that the approximations used in Hapke's model are not appropriate for a close-packed medium. Hillier and Buratti[8] have used a Monte Carlo scattering model for light scattering from a planetary surface.

The JSC-1 Martian regolith simulant sample is the <1-mm-diameter fraction of weathered volcanic ash from Pu'u Nene, a cinder cone on the island of Hawaii, which has been repeatedly cited as a close spectral analog to the bright Mars regions.[9–11] Additional information on the mineralogy,[9] reflectivity spectra,[10] and granulometry[11] has been published.

The results of various experiments involving the Martian regolith simulant on its microbial life,[12] luminescence signals,[13] particle charging,[14] and electrical discharge[15] have been reported in scientific journals. In the current paper we present very precise and accurate BRDF laboratory measurements of the same material. The reported data are intended to more completely describe the optical characteristics of JSC Mars-1 regolith simulant through its diffuse reflectance properties and should be of great interest and value to scientists working on the scattering of planetary regoliths. We have examined our results in reference to well-known scattering models.

2 Background

The BRDF is a fundamental quantity describing the reflectance properties of samples in such different applications as remote sensing,[16] computer graphics,[17] and image interpretation.[18] It describes the variation of reflectance with the illumination and scattered light directions. In many materials the surface reflectance properties are described by both specular and diffuse reflectance.

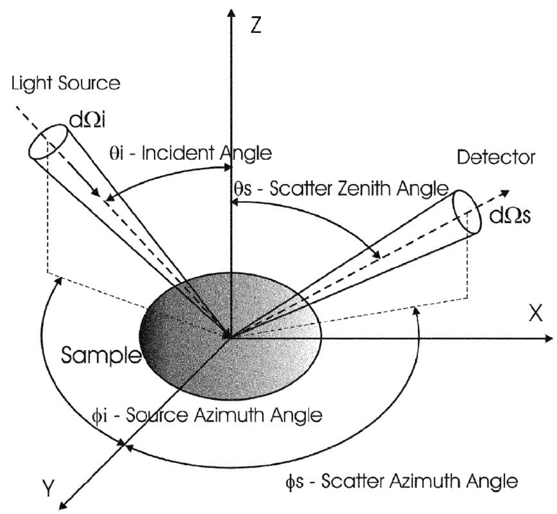

Fig. 1 Defining the BRDF in terms of the usually adopted symbols.

The BRDF is defined as the ratio of the radiance L_s scattered by a surface into the direction (θ_s, ϕ_s) to the collimated irradiance E_i incident on a unit area of the surface:[19]

$$\mathrm{BRDF} = \frac{L_s(\theta_i, \phi_i, \theta_s, \phi_s, \lambda)}{E_i(\theta_i, \phi_i, \lambda)}, \tag{1}$$

where θ is the zenith angle, ϕ is the azimuth angle, the subscripts i and s are for the incident and scattered directions, respectively, and λ is the wavelength. The BRDF angular convention is presented in Fig. 1.

In practice, the BRDF is usually described in terms of the incident power, the scattered power, and the geometry of the reflected scatter. It is equal to the scattered power per unit solid angle normalized by the product of the incident power and the cosine of the detector view angle:[19]

$$\mathrm{BRDF} = \frac{P_s/\Omega}{P_i \cos\theta_s}, \tag{2}$$

where P_s is the scattered power; Ω is the solid angle determined by the detector aperture area A and the radius R from the sample to the detector $(\Omega = A/R^2)$; P_i is the incident power; and θ_s is the scattering angle.

The scatterometer we used to perform the reported measurements is specified with a combined measurement uncertainty of 1.0% $(k=1)$, which depends on several instrument parameters.[1] The BRDF measurement uncertainty, Δ_{BRDF}, can be evaluated and expressed in accordance with NIST guidelines[20] as

$$(\Delta_{\mathrm{BRDF}})^2 = 2(\Delta_{\mathrm{NS}})^2 + 2(\Delta_{\mathrm{LIN}})^2 + (\Delta_{\mathrm{SLD}})^2 + (\Delta_{\theta s} \tan\theta_s)^2, \tag{3}$$

where Δ_{NS} is the noise-to-signal ratio, Δ_{LIN} represents the nonlinearity of the electronics, Δ_{SLD} is the error of the receiver view angle, $\Delta_{\theta s}$ is the error of the total scattering angle, and θ_s is the error of the receiver scattering angle. The error of the receiver view angle, Δ_{SLD}, is

$$(\Delta_{\mathrm{SLD}})^2 = (2\Delta_{\mathrm{RM}})^2 + (2\Delta_{\mathrm{RZ}})^2 + (2\Delta_{\mathrm{RA}})^2, \tag{4}$$

where Δ_{RM} is the error in the goniometer receiver arm radius, Δ_{RZ} is the error of the receiver arm radius due to sample Z-direction misalignment, and Δ_{RA} is the error of the receiver aperture radius. The total scattering-angle error, $\Delta_{\theta s}$, is given by

$$(\Delta_{\theta s})^2 = (\Delta_{\theta \mathrm{M}})^2 + (\Delta_{\theta Z})^2 + (\Delta_{\theta \mathrm{T}})^2, \tag{5}$$

where $\Delta_{\theta \mathrm{M}}$ is the error of the goniometer scattering angle, $\Delta_{\theta Z}$ is the error due to sample Z-direction misalignment, and $\Delta_{\theta \mathrm{T}}$ is the sample tilt error.

We used an integrating sphere attachment on the scatterometer to measure the 8-deg directional-hemispherical reflectance of JSC Mars-1. The sphere collects and spatially integrates the sample-scattered optical radiation. The sphere interior is made of Spectralon, giving it a high diffuse reflectance over the UV–visible–near-IR region of the spectrum. The reflectance is generally above 99% over a range from 400 to 1500 nm, and above 95% from 250 to 2500 nm. The sphere was designed with four ports, of which three accommodate the sample, the detector, and the entry of the incident light. The fourth port is a spare and is typically closed using a Spectralon plug. The total port area is less than 5% of the total surface area of the sphere, and radiation balance inside the sphere is established after as few internal reflections as possible. The light intensity incident on the detector should correspond to the average light intensity inside the sphere. A silicon photodiode fixed to one port of the sphere was used as a primary detector.

5 Conclusions

The BRDF and 8-deg directional-hemispherical reflectance of the Martian regolith simulant JSC Mars-1 were measured in the UV, visible, and near-IR spectral regions. The sample exhibits a wide range of BRDF values depending on the scattering geometry. Different angles of incidence from 0 to 60 deg, scattering zenith angles from 0 to 60 deg, and scattering azimuth angles 0, 90, and 180 deg were used for the full characterization of the sample. The reported experimental data show a flat BRDF response in the UV with increasing deviation from the Lambertian at higher wavelengths. The BRDF depends on both the incident and scattered light angles. The difference can be up to 13.88% for a 10-deg change of the scattering zenith angle at 500 nm. The BRDF at all wavelengths measured is symmetrical to the normal at normal incidence. Strong optical backscattering from the sample is detected, supporting the planetary regolith simulant scattering models as presented by some authors.[22] The reciprocity of the BRDF is confirmed for the material. Some 8-deg directional-hemispherical measurements are also presented. They give additional data on the material reflectance properties. The diffuse-scattering and 8-deg directional-hemispherical data from these studies are important for the analysis of spectral data obtained at future Mars space- and ground-based observations. They can be also used for calibration of existing data. The high quality of the data is supported by the fact that the measurements were done on a high-accuracy scatterometer located in a clean-room calibration facility and the results are traceable to the measurements made at NIST.